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REDUCING BUNCH DISRUPTION IN TRANSITION CROSSING BY MODIFICATION OF THE RF WAVEFORM

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Abstract

We investigate the utility of accelerating during the non-adiabatic period surrounding the time of transition with an rf waveform modified by a second or third harmonic component to eliminate rf focusing. Simulation study shows this scheme not only to control momentum spread but also to have apparent advantage with respect to microwave instability. An experimental test has been initiated in the Fermilab Main Ring using a cavity at the third harmonic of the rf.

1 Introduction

The transition energy E_{T_o} is the synchronous energy at which the beam circulation period τ_c is independent of momentum to first order in $\delta = (p - p_s)/p_s$:

$$\begin{aligned}
\frac{\Delta\tau_c}{\tau_c} &= \eta_o\delta + \eta_1\delta^2 \\
\eta_o &= \gamma_{T_o}^{-2} - \gamma_s^{-2} \qquad (\gamma = E/m_oc^2) \\
\eta_1 &= \gamma_{T_o}^{-2}(\alpha_1 - \eta_o) + \frac{3}{2}\beta_s^2\gamma_s^{-2}
\end{aligned}$$

Here p is the particle momentum, p_s is the momentum of the synchronous particle, and α_1 is the Johnson parameter. The longitudinal motion has a special character while $E_s \approx E_T$; the frequency of the longitudinal oscillation approaches zero. The motion is non-adiabatic during an interval

$$t_{na} = \pm\gamma_{T_o}\tau_c[E_T/(4\pi h\tau_c\dot{\gamma}eV|\cos\phi_s|)]^{\frac{1}{3}}$$

measured either side of transition, $t_T = 0$. For a typical Fermilab Main Ring (MR) cycle $t_{na} \approx 3.5$ ms; it will be only slightly less for the future Main Injector (MI). The transition energy is not the same for all particles:

$$\gamma_T(\delta) = \gamma_{T_o}[1 - (1/2 + \alpha_1)\delta] \ .$$

Consequently, there is a nonlinear time while some part of the bunch sees the unstable rf phase even for optimum timing of the phase switch:

$$t_{nl} = \pm(\alpha_1 + \beta^2 + 1/2)\frac{\gamma_{T_o}}{\dot{\gamma}}\delta \ .$$

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For MR parameters this time is $\sim \pm 1$ ms.

A salient feature of the beam behavior near transition is the increase in δ. Particles leading the synchronous phase receive excess energy each turn whereas those lagging receive too little; the momentum spread of the bunch increases because the off-momentum particles can not complete a phase oscillation during the non-adiabatic time. The increased momentum spread can exceed available aperture and certainly increases the nonlinear time. Much of the emittance dilution occurs after the transition crossing period because it is not possible to match the bunch resulting from the nonlinear motion.

Another characteristic pathology of this part of the acceleration cycle is microwave instability. Because the beam circulation is isochronous to first order at transition, the Landau damping of single bunch collective instability is drastically reduced. However, the growth time is difficult to calculate because the instability evolves by relative longitudinal motion, which is slow compared to the rate of change of parameters. In practice, microwave instability is a factor at transition in at least some accelerators (*e.g.*, the CERN PS[1]) and appears in tracking simulation[2].

The difficulties of the transition crossing regime may be avoided by modifying the lattice to put γ_T outside the operating range or by pulsed quadrupoles to change γ_T rapidly through the operating energy, achieving the effect of very high $\dot{\gamma}$. The latter procedure can introduce problems into the transverse motion. In any case, the cost of applying either scheme to the future MI is sufficient to encourage the exploration of alternatives.

It has been proposed[3] to provide all of the particles in each bunch with just the required accelerating voltage but no longitudinal focusing during the transition crossing period by adding a second or third harmonic to the rf wave so that the sum has constant amplitude for a period around $\pi/2$ radians. With the focusing removed just prior to transition the bunches debunch by shearing, reaching maximum width at transition. At this time the sign of η_o changes and the bunch returns to approximately its original shape during a similar time following transition. We refer to this scheme as the focus-free technique. Timing must be such that the shearing does not exceed the extent of the flattened portion of the rf wave. The phase spread attained by a bunch with momentum spread $\pm\delta$ starting t seconds before transition is[3]

$$\Delta\varphi|_{\max} = \frac{\omega_{rf} t}{{\gamma_T}^2}\left(\frac{\dot\gamma t}{\gamma_T} - \alpha_1\delta\right)\delta \ .$$

We take the focus-free interval to be the sum of the non-adiabatic and nonlinear times to find the extent of flattened waveform required. Addition of 28 % of second harmonic or 13 % of third harmonic produces a waveform flat to ±0.25 % over 70° or 54° respectively.

Second and/or third harmonic rf has been used routinely in isochronous cyclotrons to minimize energy spread,[4] but we are not aware that it has been tried near transition in an ion synchrotron. Encouraged by simulations, we have undertaken a test in the MR. Because transition crossing difficulties are evident there already at $\varepsilon_\ell \lesssim 0.2$ eVs, the third harmonic provides broad enough plateau to make a clear test. The remainder of this note is specialized to MR parameters. Results of simulations and description of the rf system are given; some preparatory observations to determine γ_T and α_1 are also described at this conference.[5] The tests are planned for the summer of 1992.

2 Modeling Studies in the Main Ring

In the table following we collect the parameters used to model the MR, not necessarily characteristic of current operation. We have selected an intermediate value for longitudinal coupling impedance, which is found from various sources to be in the range of 5–20 Ω. Figure 1 shows the evolution of ε_ℓ for four different modes of negotiating transition as calculated by the program ESME.[7] For a standard approach with fixed ϕ_s ($\phi_s = 50°$) and sudden phase jump the growth is greatest; it has the largest δ and therefore the greatest shape mis-match after transition. This mode and a duck under in which ϕ_s varies smoothly through 90° show similar microwave disruption in phasespace plots. The duck under is more successful because it leads to smaller δ. The curve showing least growth is the result of an 11.6 ms focus-free crossing from $\eta = -1.6 \cdot 10^{-4}$ to $1.5 \cdot 10^{-4}$ with

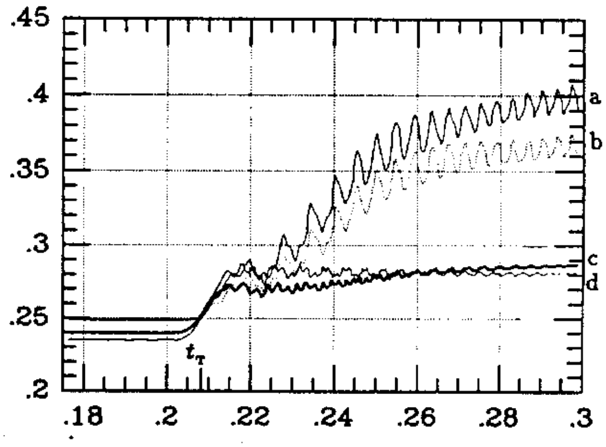

Figure 1: Longitudinal emittance [eVs] *vs.* time [s] for (a) $\phi_s = 50°$ with fast phase jump, (b) continuous phase change, (c) focus-free scheme, and (d) focus-free scheme at zero beam current

$Z_{||}/n = 0$; the frequency swing for the 159 MHz rf is 66.6 kHz. When the coupling impedance is included, the emittance growth is little changed and there is no evidence of microwave disruption of the phasespace distribution. Although the intent was to control δ, effects of beam current are also ameliorated. The debunching near transition reduces peak current at this critical time more than it reduces the local momentum spread in the bunch. Furthermore, absent rf focusing, the effect of space charge focusing approximately cancels because of its change in sign.

Table: Main Ring Parameters Used for Modeling

mean radius	1.0 km	
γ_{T_o} (nominal)	18.75	18.85 (meas.)[5]
$\dot\gamma$ @ γ_T	88.7 s^{-1}	
α_1	0.82	± 30 % [5],[6]
principal rf	53 MHz	4 MV (max)
shaping rf	159 MHz	280 kV (max)
ε_ℓ	0.2 eVs	initial
bunch intensity	3 $\cdot 10^{10}$	
coup. imp. $Z_{||}/n$	9.0 Ω	1.7 GHz cutoff

3 RF System

The 280 kV, 159 MHz system is built around a modified SPS lepton accelerating cavity prototype purchased from CERN. We have lowered the resonant frequency from 200 MHz by inserting nose cone extensions which make good electrical connection and are secure mechanically as the result of shrink-fit installation. We have added through the

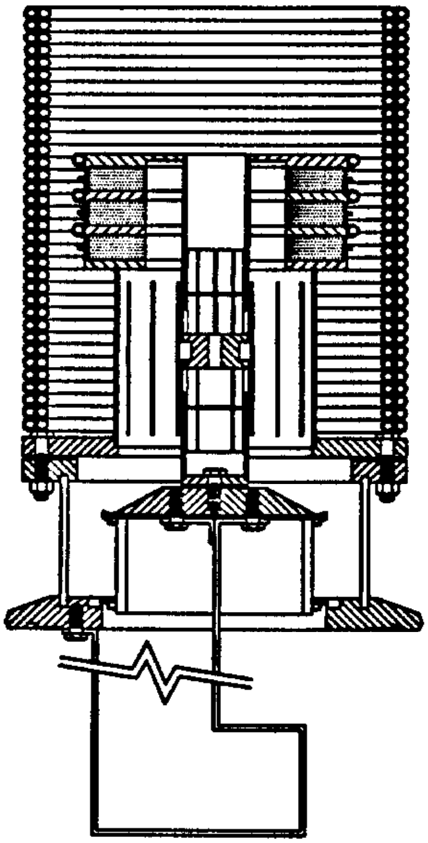

Figure 2: Transverse bias yttrium garnet tuner using three Transtek G-510 rings 127 mm (od), 34.9 mm (id), 12.7 mm thick

available flanged ports a gap short, a mechanical tuner, a power coupling loop, and a transverse biased yttrium garnet ferrite tuner ($\Delta f = 60$ kHz). A drawing of this tuner is given in Fig. 2. The cavity has been installed in the MR in place of one of the 53 MHz cavities. A power amplifier using Eimac 4CW25,000 B tetrode with a $\frac{3}{4}\lambda$ anode resonator has driven the cavity to design voltage. The low level system has been augmented to provide the two harmonics in the correct ratio and to control the amplitude of the 53 MHz system by driving the cavities in two groups with opposing correction phases. The correction phase is derived in the usual way from a radial position pickup but applied to digital phase shifters in the separate drive chains rather than to the common source. The longitudinal impedance spectrum has been measured by stretched wire and bead pull with and without short and with and without tuner bias. Neither these measurements nor observed beam excitation suggest that HOM damping will be required.

4 Conclusions

Removing the rf focusing during the non-adiabatic time around transition crossing seems a promising way to avoid the brightness or intensity limitations generally encountered in that part of the acceleration cycle. The approach may be more economical for high energy accelerators than modification of the lattice dispersion because the hardware requirements are modest and all of it is in one location. The test planned for the Fermilab Main Ring should allow a conclusive verification of the concept, the modeling studies, and the practical aspects.

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